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Journal of Hydrology, 55 (1982) 3–23

Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

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Review Paper

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A REVIEW OF CATCHMENT EXPERIMENTS TO DETERMINE THE EFFECT OF VEGETATION CHANGES ON WATER YIELD AND EVAPOTRANSPIRATION

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(Received December 29, 1980; accepted for publication January 14, 1981)

ABSTRACT

Bosch, J.M. and Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrol.*, 55: 3–23.

This summary and review of 94 catchment experiments shows that accumulated information on the effect of vegetation changes on water yield can be used for practical purposes. The direction of change in water yield following forest operations can be predicted with fair accuracy since no experiments, with the exception of perhaps one, have resulted in reductions in water yield with reductions in cover, or increases in yield, with increases in cover. The approximate magnitude of changes can also be estimated. Pine and eucalypt forest types cause on average 40-mm change in water yield per 10% change in cover and deciduous hardwood and scrub ~25 and 10 mm, respectively. Maximum changes of 660 mm were experienced at Coweeta, North Carolina. An assimilation of the collective experimental results shows that more careful design and expansion of experiments to certain rainfall regions would augment statistical inference.

INTRODUCTION

The influence of forests and forest clearfelling on water supplies have long been a cause for concern and resulted in the initiation of the first catchment experiment in 1909 at Wagon Wheel Gap in Colorado, U.S.A. The catchment experiment has since been used worldwide as a method for determining the effects of forest management practices on water yield. It has contributed considerably to our understanding of the hydrologic cycle and the effects of land use on it (Hewlett et al., 1969).

Hibbert (1967) reviewed results from 39 catchment experiments throughout the world and made the following generalizations:

- "1. Reduction of forest cover increases water yield.
2. Establishment of forest cover on sparsely vegetated land decreases water yield.
3. Response to treatment is highly variable and, for the most part, unpredictable."

Despite the cautionary wording of the third generalization, Hibbert presented a diagram showing numerous increases from 25 to 400 mm following clearcutting in forest, but virtually no decreases from any degree of cutting. Hibbert's summary has led to fairly general use of formulas for predicting forest cover effects on water yield in local regions in the U.S.A. (e.g., McMinn and Hewlett, 1975). The results of many more catchment experiments have become available since Hibbert's review. The purpose of this paper is to update Hibbert's review with the aim of exposing generalizations and trends which may elicit more careful design of catchment experiments. Fifty-five experiments were added for a total of 94.

SUMMARY

Table I contains a brief description of most of the world's paired catchment experiments, and Table II contains additional experiments which offer circumstantial evidence of the influence of catchment management on water yield.

Inference drawn from time-trend studies is weaker than that from paired-catchment experiments simply because there is no climatic control (a calibration period and a control basin) to use in separating vegetal cover effects from climatic effects. For these reasons, we have classified the results of catchment studies into a category of strong evidence (Table I), that is, studies based on deliberate experiments on paired, nested, or grouped catchments, and a category of circumstantial evidence (Table II) where studies were based on after-the-fact analyses of existing data, or less vigorous experiments on large basins.

The results from those experiments which were conducted with a control are summarized in Fig. 1, which represents maximum increases in water yield during the first five years following reduction of forest cover to some form of low cover, coppice, grass or weeds. In afforestation experiments, maximum decreases in yield following afforestation of bare land, grassland or brush have been taken as equivalent to first-year increases after clearcutting. Mean increases are reported where first-year increases were not available in the original reports.

The lines in Fig. 1 were fitted by means of the method of least squares. Correlation coefficients were low (0.650, 0.506 and 0.340 for conifer, deciduous hardwood and scrub, respectively) and the lines should be regarded with caution. They do illustrate distinct differences in the effect of changes in different vegetation types, some trends in water-yield changes with percentage change in vegetation cover and the need for more experimental results of the effect of small-percentage changes.

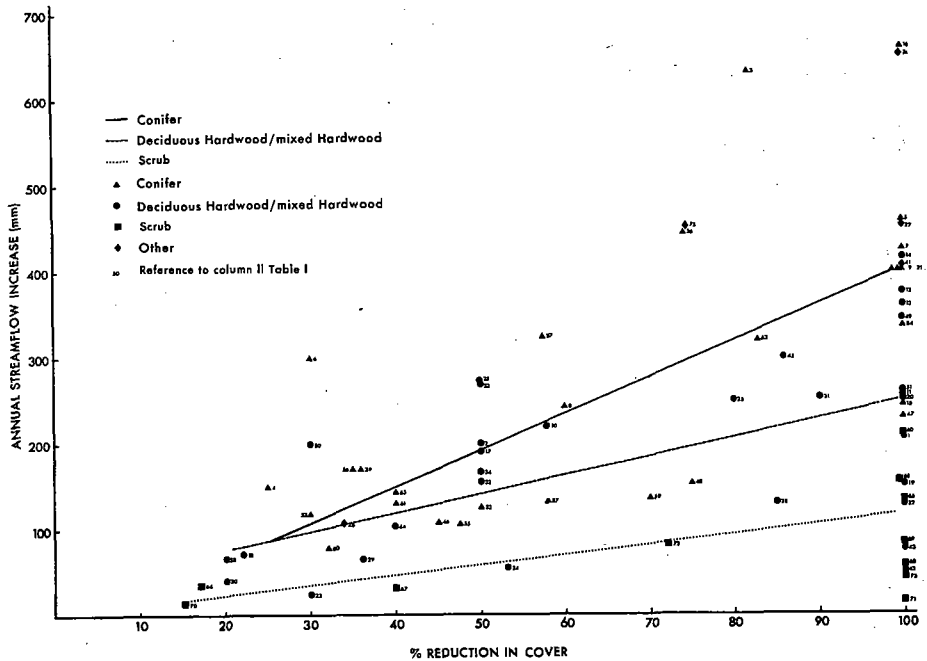


Fig. 1. Yield increases following changes in vegetation cover.

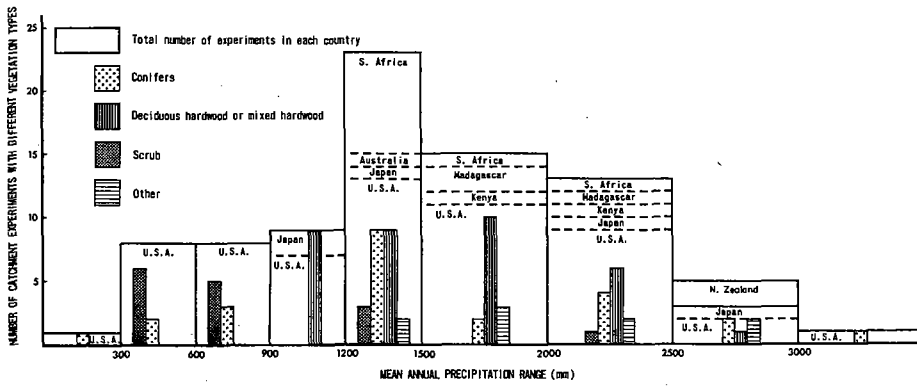


Fig. 2. The number of catchment experiments carried out in different countries, various rainfall ranges, within various broad categories of vegetation types.

Fig. 2 shows the number of experiments carried out under various classes of mean annual precipitation (MAP) and vegetation categories.

DISCUSSION

In general, the analyses and experiments listed as circumstantial in Table II, reinforce the following conclusions derived mainly from Table I; at least,

Hewlett and
Douglas
(1968)

220, 98, 108, 81,
-10, 111, 70, 91
(area)

1,632

2,270

mixed hardwoods; granitic
origin, deeply weathered
sandy clay loam up to
6 m deep

NE

1,200

144

28

TABLE I

A summary of worldwide paired catchment experiments

Catchment	Area (ha)	Mid-area elevation (m)	Aspect	Vegetation and soils	Mean annual precipitation, MAP (mm)	Mean annual streamflow (mm)	Description of treatment (percentage refers to portion of area treated unless otherwise stated)	Water-yield increases by years following treatment (1st, 2nd, unless otherwise stated) (mm)	References	Experi- ment No.
<i>Fox Creek, Oreg., U.S.A.:</i>										
FC1	59	~955		Douglas fir, western hemlock; silt loams or gravelly loams	2,730	1,750	1969-1970, 25% clearcut in 3-4 ha units	no significant increase	Harr (1976)	
FC3	71	~900		Douglas fir, western hemlock; silt loams or gravelly loams	2,730	1,750	1970-1972, 25% clearcut in 8-10 ha units	no significant increase	Harr (1980)	
<i>Japan:</i>										
Kamabuchi No. 2	3	208	SE	60% hardwood, 40% conifers	2,641 (40% snow)	2,075	1947-1948, 100% clear- felling, regrowth con- trolled by cutting until 1958; 1953-1958 re- growth burned annu- ally; 1960 contour terracing	average increase 106 (5 yr.) average increase 131 (6 yr.) average increase 218 (5 yr.)	Nakano (1971)	1
Takaragawa-Shozawa	118	1,067	SW	60% hardwood, 40% conifers	2,153	1,783	1948-1954, (50% volume selected cutting)	average increase 199 (6 yr.)		2
<i>Alsea, Oreg., U.S.A.:</i>										
Needle Branch	71	~312		Douglas fir, red alder; extremely permeable marine sandstone 60-140 cm deep	2,483	1,885	1966, 82% clearcut, burned in 1967; 5% roads	370, 520, 615, 465, 615, 530	Harris (1973; 1977); Harr (1976, 1979)	3
Deer Creek	303	~312		Douglas fir, red alder; extremely permeable marine sandstone 60-140 cm deep	2,474	1,906	1966-1967, 25% clearcut in patches, roads con- structed (5%)	110, 0, 130, maxi- mum increase 150 (non significant)		4
<i>H.J. Andrews, Oreg., U.S.A.:</i>										
1	96	700	NW	Douglas fir, western hemlock; gravelly loams and clay loams	2,388	1,376	1962-1965, 100% com- mercial clearcut and burned	462, 457, 450, 390, 330	Rothacher (1970); Harr (1976, 1979)	5
3	101	760	NW	Douglas fir, western hemlock; gravelly loams and clay loams	2,388	1,346	1962-1963, 30% clearcut and burned	150, 163, 254, 297, 226		6
6	13	~900	S	Douglas fir; unaltered volcani- clastics	2,150	1,290	1974, 100% clearcut	425, 390, 325, 290, 180		7
7	21	~900	S	Douglas fir; unaltered volcani- clastics	2,150	1,290	1974, 60% shelterwood cut	200, 240, 180, 205, 55		8
10	9	~500	S	Douglas fir, western hemlock; altered volcanoclastics	2,330	1,650	1975, 100% clearcut	195, 310, 400, 65		9
<i>Coweeta, N.C., U.S.A.:</i>										
13	16	810	NE	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	1,900	889	1940, 100% clearcut, no removal, regrowth	362, 275, 281, 255, 198, from 11th year: 140, 171, 81, 80, 96	Swift and Swank (1980)	12
							1963, experiment repeated	375, 218, 130, 100, 70, from 11th year: 180, 120, 0, 140, 30	Swank and Helvey (1970)	13

28	144	1,200	NE	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	2,270	1,532	1962-1964, 51% clearcut, 22% thinned (65% basal area)	220, 98, 108, 31, -10, 111, 70, 91	Hewlett and Douglass (1968); Douglass and Swank (1976)	10
37	44	1,280	NE	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	2,244	1,583	1963, 100% clearcut, subsequent natural re-growth	255, 100, 85, 0, 0, 26, 100, 75	Swank and Helvey (1970); Swift and Swank (1980)	11
17	14	885	NW	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	1,895	775	1941, 100% clearcut, re-growth cut annually 1956, 100% planted with pine	414, 337, 281, 160, 228 maximum reduction 248 (relative to hardwood) maximum reduction 662 (relative to bare ground)	Swank and Miner (1968); Johnson and Kovner (1954); Swank and Douglass (1974)	14 15 16
22	34	1,035	N	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	2,068	1,275	1955, 50% poisoned in alternate 10-m strips, no removal, regrowth restricted	189, 155, 130, 112, 100	Hewlett and Hibbert (1961)	17
19	28	960	NW	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	2,001	1,222	1949, 22% basal area cut, under storey only	71, 64, 55, 47, 39	Johnson and Kovner (1956)	18
1	16	840	S	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	1,725	739	1956-1957, 100% clear-cut, partly burned 1957, pine planted	150, 15, 60, 32 maximum reduction 250 (relative to hardwood); maximum reduction 400 (relative to bare ground)	Swank and Miner (1968); Swank and Douglass (1974); Coweeta Laboratory, unpublished data (1979)	19 20 21
3	9	825	SE	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	1,814	607	1940, 100% cleared for agriculture	127, 95, 59, 113, 80	Johnson and Kovner (1956)	22
10	86	975	SE	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	1,854	1,072	1942-1956, 30%, basal area cut by uncontrolled logging	25 mm average increase	Johnson and Kovner (1956)	23
41	29	1,065	SE	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	2,029	1,285	1955, 53% basal area cut by selective logging	55 mm average increase	Johnson and Kovner (1956)	24
40	20	1,035	SE	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	1,946	1,052	1955, 27% basal area cut by selective logging	not significantly different	Johnson and Kovner (1956)	
6	9	793	NW	mixed hardwoods; granitic origin, deeply weathered sandy clay loam up to 6 m deep	1,854	838	1958-1960, 80% converted to grass 1966, grass killed	15 (fertilized grass); 265 relative to hardwood; 250 relative to grass	Coweeta Laboratory, unpublished data (1979)	25

TABLE I (continued)

Catchment	Area (ha)	Mid-area elevation (m)	Aspect	Vegetation and soils	Mean annual precipitation, MAP (mm)	Mean annual streamflow (mm)	Description of treatment (percentage refers to portion of area treated unless otherwise stated)	Water-yield increases by years following treatment (1st, 2nd, unless otherwise stated) (mm)	References	Experiment No.
<i>Kenya, East Africa:</i>										
Kericho Sambret	688	2,200	NW	high montane and bamboo; phenolite lava, deep friable clay	1,905	416	1959-1960, 34% cleared for tea plantation	103	Pereira (1962, 1964)	26
Kimakia A	35	2,440	S	high montane and bamboo; phenolite lava, deep friable clay	2,014	568	1966, 100% cleared, pine planted	457, 229, 178		27
<i>Fernow, W. Va., U.S.A.:</i>										
1	30	755	NE	mixed hardwoods; sandstone and shale, stoney silt loam, 1-1.5 m deep	1,524	584	1957-1958, 85% basal area commercial clear-cut, regrowth	130, 86, 89	Reinhart et al. (1963); Patric and Reinhart (1971); Patric (1980)	28
2	15	780	S	mixed hardwoods; sandstone and shale, stoney silt loam, 1-1.5 m deep	1,500	660	1957-1958, 36% basal area by diameter-limit cut, regrowth	64, 36		29
5	36	780	NE	mixed hardwoods; sandstone and shale, stoney silt loam, 1-1.5 m deep	1,473	762	1957-1958, 20% basal area removed by extensive-selection cut, regrowth 1968, treatment repeated, 14% basal area	36 no significant increase		30
3	34	805	S	mixed hardwoods; sandstone and shale, stoney silt loam, 1-1.5 m deep	1,500	607	1957-1958, 13% basal area removed by intensive-selection cut, regrowth 1963, 8% of basal area removed, same method 1968, 6% of basal area removed, same method 1969-1970, 91% of area clearcut	8 (non significant) no significant influence no significant influence 253, 85, 60, 80		31
7	24	800	NE	mixed hardwoods; sandstone and shale, stoney silt loam, 1-1.5 m deep	1,469	788	1963, 50% upper half area cut, timber removed, regrowth not permitted 1967, lower 50% cut	155, 145 251, 261		32 33
6	22		SE	mixed hardwoods; sandstone and shale, stoney silt loam, 1-1.5 m deep	1,440	493	1964, lower 50% cut, regrowth not permitted 1968, upper 50% cut	165, 142 259		34 35
<i>Cathedral Peak, South Africa:</i>										
C II	190	2,073	NE	<i>Themeda</i> grassland; basaltic lava with deeply weathered saprolite	1,400	~650	1951, 74% afforested with <i>Pinus patula</i>	maximum reduction 440 (after 22 yr.) mean reduction 257	Nänni (1970a); Bosch (1979)	36

C III	142	2,080	NE	<i>Themeda</i> grassland; basaltic lava with deeply weathered saprolite	1,400	~650	1957, 84% afforested with <i>P. patula</i>	13 mm reduction (15 July-2 Sept.)		
C IX	62	1,900	SE	<i>Themeda</i> grassland; basaltic lava with deeply weathered saprolite	1,400	~650	protected against fire for 12 yr. 20% invasion by scrub	no significant change		
<i>Jonkershoek, South Africa:</i>										
Bosboukloof	200	532	SW	sclerophyllous scrub (fynbos)	1,390	590	1940, 57% afforested with <i>P. radiata</i>	maximum reduction 325 (after 23 yr.); mean reduction 270	Wicht (1943); Van der Zel and Kruger (1975); Van Wyk (1977)	37
Biesievlei	27	398	SW	sclerophyllous scrub (fynbos)	1,400	660	1948, 98% afforested with <i>P. radiata</i>	maximum reduction 400 (after 15 yr.); mean reduction 313		38
Tierkloof	157	682	SW	sclerophyllous scrub (fynbos)	1,809	1,100	1956, 36% afforested with <i>P. radiata</i>	maximum reduction 170 (after 8 yr.); mean reduction 130		39
Langrivier	246	819	SW	sclerophyllous scrub (fynbos)	2,242	1,600	protected against fire	maximum reduction 211 (after 20 yr.); mean reduction 125		40
Lambrechtsbos A	31	500	SW	sclerophyllous scrub (fynbos)	1,393	656	natural growth (26 yr.)	no significant influence		
Lambrechtsbos B	65	600	SW	sclerophyllous scrub (fynbos)	1,451	460	1961, 84% afforestation	no significant effect after 8 yr.		
<i>Mokobulaan, South Africa:</i>										
C A	26	141	E	seasonally dry grassland; deeply weathered shale with very shallow clayey sand soils	1,150	173	1969, 100% afforested with <i>Eucalyptus</i>	maximum reduction 403 (after 6 yr.); mean reduction 340	Van Lill et al. (1980)	41
<i>Northern Mississippi, U.S.A.:</i>										
WS II	1		E	mixed hardwood; deep soils, silt loam to sandy loam	1,354		1963-1964, undergrowth burned, trees killed by herbicide application (100%)	31, 26, 47	Ursic (1970)	42
WS III	1		E	mixed hardwood; deep soils, silt loam to sandy loam			1963-1964, undergrowth burned, trees killed by herbicide application (100%)	69, 34, 75		43
<i>Upper Bear Creek, Ala., U.S.A.:</i>										
XFI	53			pine and hardwood; fine sandy loam surface with sandy clay subsoil	1,397		1971-1972, 30% clearcut, additional 22% selective cut, burned residual poisoned, pines planted	102, 36	Batson (1979)	44

60

TABLE I (continued)

Catchment	Area (ha)	Mid-area elevation (m)	Aspect	Vegetation and soils	Mean annual precipitation, MAP (mm)	Mean annual streamflow (mm)	Description of treatment (percentage refers to portion of area treated unless otherwise stated)	Water-yield increases by years following treatment (1st, 2nd, unless otherwise stated) (mm)	References	Experi- ment No.
<i>Upper Bear Creek, Ala., U.S.A. (continued):</i>										
XF2	63			pine and hardwood; fine sandy loam surface with sandy clay subsoil			1969-1970, 86%, con- version to pine after commercial cut, poisoning and burning	297, 244, 91		45
<i>Alum Creek, Ark., U.S.A.:</i>										
WS2	1	412	NE	pine with hardwood under- storey; stoney loam soils 0.75-1 m deep	1,333	163	1970, 46% thinned, under- growth killed by herbi- cide application	107, 58, 89, 68	T. Rogerson (pers. com- mun., 1979)	46
WS3	1		NE	pine with hardwood under- storey; stoney loam soils 0.75-1 m deep			1970, 100% clearcut sprayed annually for 3 yr.	226, 142, 114, 146		47
<i>Western Tennessee, U.S.A.:</i>										
Pine Tree Branch	36	160	E	23% mixed hardwoods in 1941; sandy silt loams	1,230	256	1946, 75% reforested, mostly pine	reduction of 76-152 (after 16 yr.)	T.V.A. (1961)	48
<i>Hubbard Brook, N.H., U.S.A.:</i>										
WS2	16		S	hardwood; coarse textured sands and sandy loams, 1.7 m deep	1,219	~710	1965, 100% cleared, re- growth controlled 1969, regrowth allowed	343, 274, 240	Hornbeck et al. (1970)	49
WS5	35		S	hardwood; coarse textured sands and sandy loams, 1.7 m deep			1970, 30% cut in 25-m width strips alternating with 25-m width uncut strips	200, 500	Hornbeck (1975)	50
<i>Grant Forest, Ga., U.S.A.:</i>										
WS18	33	165	SW	hardwood; sandy loam over- lying loamey B horizon	1,219	467	1974-1975, 100% clear- cut, roller chopped twice, and pine planted by machine	254	Hewlett (1979)	51
<i>Eastern Tennessee, U.S.A.:</i>										
White Hollow	694	410	SE	65% mixed hardwoods and pine in 1934; limestone, silt loams	1,184	460	1934-1942, 34% refor- ested, mostly pine	no detectable change	T.V.A. (1961)	
<i>Coyote Creek, Oreg., U.S.A.:</i>										
1	69	~900		Douglas fir, mixed conifers; well-drained gravelly loam, 150 cm deep	1,230	627	1971, individual trees rep- resenting 60% of basal area removed; $\pm 2\%$ roads	60 (average over 5 yr.); 1st-year increase non- significant	Harr (1976); Harr et al. (1979)	52
2	68			Douglas fir, mixed conifers; well-drained gravelly loam, 150 cm deep			30% patch-cut; $\pm 2\%$ roads; slash disposal	68, 100, 119, 82, 80		53

3	50			Douglas fir, mixed conifers; well-drained gravelly loam, 150 cm deep			100% clearcut; roads; slash disposal	360, 292, 335, 231, 269		54
<i>Adirondacks, N.Y., U.S.A.:</i>										
Sacandaga River	127,200	575		northern hardwoods with conifers; glacial till, sandy loam <1 m deep	1,143 (some snow)	770	1912-1950, basal area increased from 17 to 28 m ² ha ⁻¹	196 reduction (after 38 yr.)	Eschner (1965)	
<i>Central New York, U.S.A.:</i>										
Sage Brook	181	525	SE	mixed hardwoods and conifers; shales and sandstones over- lain by glacial till, silt loams up to 3 m deep	974	535	1932, 47% reforested, conifers	106 reduction (after 26 yr.)	Schneider and Ayer (1961)	55
Cold Spring Brook	391	565	S	mixed hardwoods and conifers; shales and sandstones over- lain by glacial till, silt loams up to 3 m deep	1,030	616	1934, 35% reforested, conifers	172 reduction (after 24 yr.)		56
Shacklam Brook	808	520	S	mixed hardwoods and conifers; shales and sandstones over- lain by glacial till, silt loams up to 3 m deep	1,030	627	1931-1939, 58% refor- estation, conifers	130 reduction (after 24 yr.)		57
<i>Leading Ridge, Pa., U.S.A.:</i>										
WS2	43	358	S	mixed hardwood; deep silt loam underlain by shale at bottom, and sandstone higher up	1,004 (some snow)	321	1966-1967, 20% (lower slopes) clearcut	68	Lynch (1969)	58
<i>Coshocton, Ohio, U.S.A.:</i>										
172	18	350	SW	30% hardwoods in 1938; sedi- mentary silt loams	970 (little snow)	300	1938-1939, 70% refor- ested, mostly pine	135 reduction (after 19 yr.)	Harrold et al. (1962)	59
<i>Sierra Ancha, Ariz., U.S.A.:</i>										
North Fork, Workman Creek	100	2,225	SW	conifer (ponderosa pine); quartzite, clay loam up to 5 m deep	813	86	1953, <1% cut (riparian vegetation) 1958, 32% cleared (moist site), grass seeded 1966-1969, 40% cleared (dry site) and residual burned (total 73% cleared)	non significant 13, 61, 15, 48, 30 48, 130, 100, 80, 25	Rich et al. (1961); Rich and Gottfried (1976); Hib- bert (1979)	60 61
South Fork, Workman Creek	129	2,165	NW	conifer (ponderosa pine); quartzite, clay loam up to 5 m deep	813	87	1953-1957, 45% of forest basal area removed by selection cuts, thin- nings, roads and fire 1966, 83% of watershed cleared to establish pure-pine forest, re- maining 17% thinned	significant increase only in wettest years maximum ±320 mm average increase 93 mm		62

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<i>White Spar, Ariz., U.S.A.:</i>										
B	100	1,910	SE	chaparral; fine grained granite	549	34	1967, shrub on 15% chemically treated 1974-1976, shrub on 20% (strip around watershed periphery) chemically	average increase 13 (10 yr.) no detectable effect	Hibbert (1971, 1979); Hibbert and Ingebo (1971)	70

TABLE I (continued)

Catchment	Area (ha)	Mid-area elevation (m)	Aspect	Vegetation and soils	Mean annual precipitation, MAP (mm)	Mean annual streamflow (mm)	Description of treatment (percentage refers to portion of area treated unless otherwise stated)	Water-yield increases by years following treatment (1st, 2nd, unless otherwise stated) (mm)	References	Experi- ment No.
<i>Frazer, Colo., U.S.A.:</i>										
Fool Creek	289	3,200	N	lodgepole pine and spruce-fir; soils have schistic and granitic origin, very perme- able	762 (75% snow)	283	1954-1966, 40% com- mercial cut in strips, regrowth	109, 147, 89, 76, 91, reduction after 21st, 22nd and 23rd year: 28, 18, 61, respectively	Alexander and Watkins (1977); Troendle (1980)	63
<i>San Dimas, Calif., U.S.A.:</i>										
Monroe Canyon	354	840	S	chaparral with woodland ripar- ian vegetation along streams; granitic, rocky sandy loam	648	64	1958, 1.7% cut (riparian vegetation)	May-Dec. 6 mm; Jan.-April 4 mm	Rowe (1963)	
<i>Castle Creek, Ariz., U.S.A.:</i>										
West Fork	364	8,207	SE	conifer (ponderosa pine); soil of igneous origin	639	71	1965-1967, 16.6% cut and remainder thinned	10, 36	Rich (1968, 1972); Rich and Thomp- son (1974)	64
<i>Placer County, Calif., U.S.A.:</i>										
WS C	5	168	N	oak woodland; shallow residual loams, clay loams	635	145	1963-1966, 99% of trees and brush killed	111, 154, 75	Lewis (1968); Burgy and Papazafiriou (1971)	65
<i>Three Bar, Ariz., U.S.A.:</i>										
C	39	1,160	N	chaparral; coarse granite	638	58	1959, burned completely, grass seeded 1960-1964, 100% chemi- cally treated, converted to grass	average increase 132 (16 yr.)	Hibbert (1971, 1979); Hibbert and Ingebo (1971); Ingebo and Hibbert (1974); Hib- bert et al. (1975); A.R. Hibbert (pers. com- mun., 1980)	66
B	19	1,080	N	chaparral; coarse granite	582	11	1959, burned 100%, grass seeded, regrowth 1965, shrubs on 40% (NE slopes) chemically treated 1972, remaining 60% chemically treated	average increase 30 (7 yr.) average increase fol- lowing 100% treatment: 52 (5 yr.)		67 68
F	28	1,300	N	chaparral; coarse granite	681	36	1959, burned 100%, grass seeded, regrowth 1969, 100% chemically treated	average increase 81 (8 yr.)		69

White Spar, Ariz., U.S.A.:										
B	100	1,910	SE	chaparral; fine grained granite	549	34	1967, shrub on 15% chemically treated 1974-1976, shrub on 20% (strip around watershed periphery) chemically treated	average increase 13 (10 yr.) no detectable effect	Hibbert (1971, 1979); Hibbert and Ingebo (1971); Ingebo and Hibbert (1974); Hibbert et al. (1975); A.H. Hibbert (pers. commun., 1980)	70
Natural Drainages, Ariz., U.S.A.:										
A	5	1,420	SE	marginal chaparral; diabase and quartzite	452	34	1954, 100% chemically controlled	non-significant effect	Hibbert (1971, 1979); Hibbert and Ingebo (1971); Ingebo and Hibbert (1974); Hibbert et al. (1975); A.H. Hibbert (pers. commun., 1980)	71
C	5	1,420	SE	marginal chaparral; diabase and quartzite	452	43	1954, 100% chemically controlled	average increase 13 (17 yr.)		
Beaver Creek, Utah, U.S.A.:										
I	124	1,700	W	juniper-pinyon forest; volcanic rock, soils stoney clay ~60 cm deep	457	20	1963, 100% cleared by cabling and burning	no significant change	Brown (1971); Clary et al. (1974); Hibbert (1979)	72
3	146	1,600	W	juniper-pinyon forest; volcanic rock, soils stoney clay ~60 cm deep	457	18	1968, 83% overstorey killed with herbicides	10, 30, 1, 4		
Wagon Wheel Gap, Colo., U.S.A.:										
B	81	3,110	NE	84% aspen and conifer; augite, quartzite, rocky clay loam	536 (50% snow)	157	1919, 100% clearcut, some removal, slash burned, regrowth	34, 47, 25, 22, 13	Bates and Henry (1928); Reinhart et al. (1963)	73
Maimai, New Zealand:										
M7	4.14	~300	S	mixed beech (<i>Nothofagus</i>) — podocarp — hardwood forest; shallow stoney silt loams — podsolized yellow brown earths	2,600	1,500	100% clearfelled, burned, planted with <i>P. radiata</i>	650 mm in 1st year	Pearce et al. (1976)	74
M9	8.26	~310	S	mixed beech (<i>Nothofagus</i>) — podocarp — hardwood forest; shallow stoney silt loams — podsolized yellow brown earths	2,600	1,500	75% clearfelled, burned, planted with <i>P. radiata</i>	540 mm in 1st year	Pearce et al. (1980)	75

TABLE II

A summary of climatic uncontrolled catchment experiments

Catchment	Area (ha)	Mid-area elevation (m)	Aspect	Vegetation and soils	Mean annual precipitation, MAP (mm)	Mean annual streamflow (mm)	Description of treatment (percentage refers to portion of area treated unless otherwise stated)	Water-yield increases by years following treatment (1st, 2nd, unless otherwise stated) (mm)	References
<i>Japan:</i>									
Kamikawa-Kitatani	645	600	W	60% hardwood, 40% conifers	1,438 (35% snow)	808	1954-1958, 90% logged after typhoon damage	average increase 164 (after 2 yr.)	Nakano (1971)
Tatsunokuchiyama-Minamitani	23	160	NW	natural forest of Akamatsu with Hinoki artificial stand (20%)	1,153	293	100% clearcut and logging	209	Nakano (1971)
Kitatani	17	150	W	natural forest of Akamatsu with Hinoki artificial stand (20%)	1,113	290	100% clearcut and logging; natural forest	205	
<i>Madagascar:</i>									
D2, D3	7-39			natural forest	~2,100	~730	natural forest	yields 250 mm less water than a Savoka brush covered catchment	Bailly et al. (1974)
D5	13			<i>Eucalyptus robusta</i>	~1,600	~700	<i>Eucalyptus robusta</i>	yields 400 mm less water than a natural forest	
<i>Melbourne, Vic., Australia:</i>									
Graceburn	2,500	120-1,200		<i>Eucalyptus</i> forest; igneous rocks, 3-4 m deep clay to clay loam	~1,460	850	1939, fire caused regrowth	average reduction over 21 yr.: 240	Langford (1976)
Watts	10,300			<i>Eucalyptus</i> forest; igneous rocks, 3-4 m deep clay to clay loam		930	1939, fire caused regrowth	average reduction over 21 yr.: 220	
Donnelly's	1,430			<i>Eucalyptus</i> forest; igneous rocks, 3-4 m deep clay to clay loam		470	1939, fire caused regrowth	average reduction over 21 yr.: 145	
Coranderrk	1,860			<i>Eucalyptus</i> forest; igneous rocks, 3-4 m deep clay to clay loam		1,160	1939, fire caused regrowth	average reduction over 21 yr.: 155	
<i>Western Australia:</i>									
Wungong Brook	14,600	~150		dominated by <i>E. marginata</i> and <i>E. calophylla</i> ; soils dominated by lateritic materials	~1,100	~190	<i>E. marginata</i> dieback, logging, burning	increases observed which were ascribed to dieback	Batini et al. (1980)
<i>Entiat, Wash., U.S.A.:</i>									
McCree	514	1,348	SE	ponderosa pine and Douglas fir; base rock Chelan Batholith, soil sandy loam	579	112	1970, burned completely	91	Helvey (1973, 1980)
Burns	563	1,403		ponderosa pine and Douglas fir; base rock Chelan Batholith, soil sandy loam	597	155	1970, burned completely	74	

Fox	473	1,496	ponderosa pine and Douglas fir; base rock Chelan Batholith, soil sandy loam	175	1970, burned completely	112, 472 (2nd yr. abnormally wet)	
<i>Alberta, Canada:</i>							
Hinton	1,497 (average)	1,440	spruce, lodgepole pine	~520	~50% clearfelling in alternate 16- and 25-ha strips	average increase 40	Swanson and Hillman (1977)
<i>Meeher, Colo., U.S.A.:</i>							
White River	197,400		conifers (spruce)	265	1941-1946, insects killed up to 80% of timber on 30% of area	average increase 68 (5 yr.)	Love (1955)
<i>Southwestern Washington, U.S.A.:</i>							
Naselle River	14,245	275	Douglas fir, western hemlock; silty-clay loam and stoney loam, 2 m deep	3,300	2,690	1916-1954, 64% area logged at rate of 2%/yr., regrowth	no detectable change Martin and Tinney (1962)

no carefully analysed time trend or single basin study to date mitigates against the general summary that follows.

Fig. 1 shows that the results summarized by Hibbert (1967) are little altered by the addition of 55 experiments to the world's store of information on vegetal effects on water yield and evapotranspiration. Variation in results is extreme but some general conclusions are justified. No experiments in deliberately reducing cover caused reductions in yield, nor have any deliberate increases in cover caused increases in yield. The only results that partly contradict this conclusion, is that of a study by Langford (1976) on the effect of *Eucalyptus regnans* regrowth on water yield after a bush fire in Australia. Langford concluded that there was no significant increase in water yield immediately after a stand of *Eucalyptus* was burned down and reported reductions in streamflow from three to five years after the burn, when regrowth was established.

This updating of Hibbert's (1967) summary of catchment experiments reinforces his first two generalizations, but leaves us less inclined to support his third, that water-yield response to afforestation and deforestation is unpredictable. The question is: how well do we need to predict these changes?

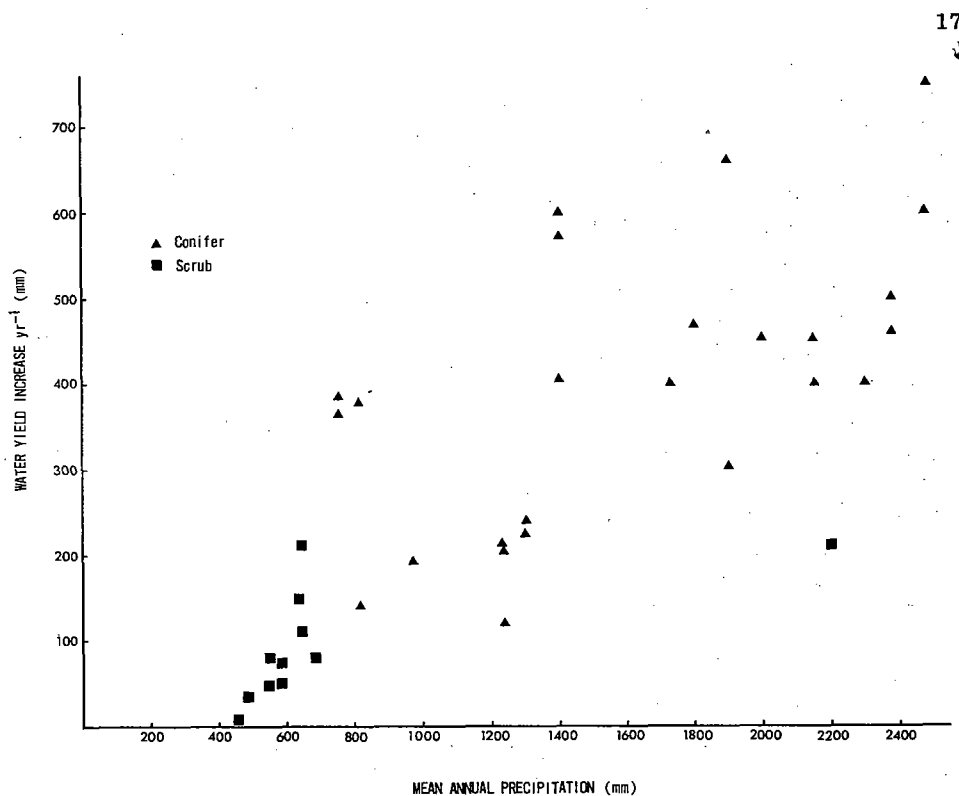
The inference on this review is that coniferous forest, deciduous hardwood, brush and grass cover have (in that order) a decreasing influence on water yield of the source areas in which these covers are manipulated.

Coniferous and eucalypt cover types cause ~ 40 mm change in annual water yield per 10% change in forest cover. Deciduous hardwoods are associated with a 25-mm change in yield per 10% change in cover, while 10% changes in brush or grass lands seem to result in ~ 10 mm change in annual yield. Error limits cannot be set upon these coefficients, but the order and magnitude of the changes shown in Fig. 1 are clear and convincing.

Reductions in forest cover of less than 20%, an experiment seldom attempted anyway, apparently cannot be detected by measuring streamflow, that is, by what has been termed the "hydrometric method". McMinn and Hewlett (1975) have discussed this problem and suggested that logically the effect of zero treatment must be zero and therefore we must carry forward the assumption that ever smaller percentage reductions in forest cover will produce effects approaching zero increases in expected water yield.

The review showed certain other trends which may account for some of the variability in the results depicted in Fig. 1.

Streamflow response to deforestation or afforestation depend both on the region's MAP and on the precipitation for the year under treatment. Yield changes, whether increases due to cutting or decreases due to planting, are greatest in high-rainfall areas. The effect of clearcutting is, however, shorter-lived than in low-rainfall areas due to rapid regrowth of vegetation. On the other hand, the annual change due to treatment in *high*-rainfall areas seems independent of the variation of rainfall from year to year. Fig. 3 shows the distribution of water-yield changes after clearcutting of conifers and scrub as a function of annual precipitation. (Yield changes given in Table I were



the specific year of treatment. Because of the great variability in precipitation from year to year, additional years of calibration and treatment are needed to measure the effect of wet vs. dry years on the expected changes in streamflow in dry areas. It is often in these areas that conflicts between source area and downstream uses of water first develop and forest practice first comes under criticism.

Decreases in water yield following afforestation seem to be proportional to the growth rate of the stand while gains in water yield after clearfelling diminish in proportion to the rate of recovery of the vegetation.

The highest annual change in water yield or any experimental catchment caused by manipulation of the forest stands and types was 660 mm yr^{-1} , reported from the experiment on Coweeta catchment 17, North Carolina, U.S.A. This record effect is not an isolated phenomenon, however; other cuttings and plantings have suggested change of similar magnitude in Oregon, U.S.A., and South Africa.

A number of papers have expressed the view that yield increases following partial cuttings are related to the location of such cuttings in respect to the source area of streamflow.

The average size of the catchments used in experiments to determine the effects of vegetal cover on water yield and evapotranspiration is $\sim 80 \text{ ha}$, ranging from 1 to 2500 ha. Depending on topography, climate and soils, a catchment of 50–100 ha seems the most usual choice for an experiment in which the input and output of water is to be balanced and conclusions are to be drawn about the results of changes in vegetal cover. If the basin is too small, errors from the failure of the subsurface water divides to match surface-water divides can be substantial. As a consequence, water-yield changes per unit area can be seriously distorted. On the other hand, as the catchment becomes larger, it becomes increasingly difficult to control treatments, to estimate precipitation, and to measure streamflow accurately. Since the cost of a controlled experiment becomes excessive on large catchments, most water-yield reports on large basins have been based on time-trend analyses, often using existing data.

CONCLUSION

Accurate summary of, and inference from, catchment experiment results are admittedly complicated by the variation in experimental conditions and the different ways in which results are presented. It has, however, been shown that catchment results are influenced by certain general trends which could account for some of the variation. Careful design and selection of experimental sites can augment statistical inference from results.

Probabilistic interpretation is possible if a sufficient number of results are available; however, statistical inference will remain difficult so long as treatments cannot be described as drawn from an identifiable (definable) popu-

lation of catchments and treatments. The design of catchment experiments and the nature of inference drawn from them, has received all too little attention. For example, an *International Guide for Research and Practice on Representative and Experimental Basins*, issued by U.N.E.S.C.O. (Toebe and Ouryvaev, 1970), had virtually nothing to say about the nature of inference to be drawn from one or a series of experimental catchments, although the management of basin networks, instrumentation, data processing and analysis were exhaustively treated. Hewlett et al. (1969), Hewlett (1970) and Hewlett and Pienaar (1973) have discussed the design and inference of catchment experiments, but much remains to be done before these questions can be settled.

While we hesitate to offer derived functions relating water-yield changes to forestry practices in this paper, we do feel that the accumulated evidence presented in Fig. 1 can be used for some practical purposes, such as estimating for planning purposes the direction and approximate magnitude of past and future changes in streamflow as a function of forestry operations. This has, for example, been done by Swanson and Hillman (1977) for Alberta, Canada. Also despite the lack of statistical rigour in the design and analysis of catchment experiments on water yield, conclusions drawn from them have been incorporated into simulators that purport to include the effects of vegetal cover on yield, for example, the PROSPER model (Goldstein et al., 1974), in the U.S.A. and the Pitman (1978) model in South Africa.

Conclusions from experimental data have also been used for models to predict the effect of afforestation on water supplies, such as in South Africa (Nänni, 1970b).

Regardless of the problem of statistical inference from such a scattered set of experimental catchments, some valuable information about vegetal effects on water yield and evapotranspiration is available and ready for use in planning.

At least it may be reasonably argued that results from repeated experiments are more convincing than conclusions based on computation from evapotranspiration theory or on correlations between uncontrolled variables.

ACKNOWLEDGEMENTS

The authors thank the following colleagues who generously supplied unpublished data and assisted in editing Table I: A.R. Hibbert, J.E. Douglass, C.A. Troendle, R.D. Harr, C. Bailly, S. Kunkle, C.L. O'Loughlin and F.J. Kruger.

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